

Do quantum nonlocal correlations imply information transfer?-

A simple quantum optical test.

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In order to understand whether nonlocality implies information transfer, a quantum optical experimental test, well within the scope of current technology, is proposed. It is essentially a delayed choice experiment as applied to entangled particles. The basic idea is: given two observers sharing position-momentum entangled photons, one party chooses whether she measures position or momentum of her photons after the particles leave the source. The other party should infer her action by checking for the absence or presence of characteristic interference patterns after subjecting his particles to certain optical pre-processing. An occurrence of signal transmission is attributed to the breakdown of complementarity in incomplete measurements. Since the result implies that the transferred information is classical, we discuss some propositions for safeguarding causality.

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I. INTRODUCTION

Quantum information has opened up a new era in recent times both in fundamental and applied physics. Its nonclassical resources of quantum superposition and entanglement are at the heart of powerful future applications in communication [1] and computation [2]. And yet, the fundamentally very important question whether the correlated measurements on entangled systems imply an "action-at-a-distance" effect remains somehow unclear. Einstein, Podolsky and Rosen (EPR) thought that it did, which was the basis of their claim of quantum mechanical incompleteness [3]. Quantum nonlocal correlations have been confirmed in experiments since the mid-1980's performed both on spin entangled systems [4], based on the Bohm version [5] of the EPR thought-experiment, which are shown to violate Bell's inequality [6], and also on systems entangled in continuous variables (Refs. [7,8] and references therein), where nonlocality is manifested in multi-particle interferences.

Bell's celebrated theorem [6] tells us only that any realistic model of quantum mechanics should be nonlocal. Informed opinions diverge between on the one hand the view that quantum nonlocality implies no information transfer, but only a change in the mutual knowledge of the two nonlocal systems, to the acknowledgement on the other hand of a tension between quantum theory and special relativity [9]. The tension stems from the possibility that the nonlocal correlations might imply a superluminal transfer of information. A majority of physicists in the field, it would seem, accept the scenario of a spacelike but causal enforcement of correlation, as for example in quantum dense coding [10]. In this view, entanglement cannot be used to transmit classical signals nonlocally because statistically the single particle outcome at any one particle is not affected by measurements on its entangled parties [11]. This understanding is echoed in statements of "a deep mystery" [12], and "peaceful coexistence" [13] between quantum nonlocality and special relativity.

In the present article, we propose a simple quantum optical experiment whose aim is to test in a philosophically unpredisposed way whether information transfer occurs in nonlocal systems.

II. A PRACTICAL EXPERIMENT

Figure 1 presents a 'folded out' plan of an experiment in which two observers, designated Alice and Bob, share entangled photons from a nonlinear crystal pumped by a suitable laser (eg., Ar laser in λ 351.1 nm). The correlated photons are produced by spontaneous parametric down-conversion (SPDC) [8]. Photons not down-converted are filtered out (not shown in Figure 1), leaving only entangled photon pairs to be shared between Alice and Bob.

Alice's observes her photons through a lens of focal length f . It is positioned at distance $2f$ from the EPR source. By classical optics, coplanar rays that are parallel in front of her lens converge to a single point on the focal plane. A detection by Alice at some point on the focal plane on her side of the lens implies that Bob's photon is left in a definite momentum state, but with its point of origin in the source indeterminate as expected on basis of the uncertainty principle. This has indeed been confirmed by observing an interference pattern in Bob's photons detected in coincidence with Alice's momentum measurement [15].

On the other hand, by positioning her detector at some point on the image plane of her lens, Alice images the source, and hence measures the point of origin of her photon, but here the momentum with which it left the source remains indeterminate. Bob's photon is also left in a position eigenstate, with the position of its detection being correlated with that of Alice's coincidentally detected photon [15]. Bob is equipped with a Young's double-slit interferometer and a direction filter permitting only horizontal momenta to reach Bob's interferometer. The filter consists of two convex lenses, of radius R and focal length g , sharing a focal plane. A diaphragm is placed at this plane, perforated with a small hole, of diameter h , at the point where the principal axis of the lenses intercepts the diaphragm.

Provided $h/g \ll \lambda/s$, where s is the interferometer slit-separation, the permitted deviation from horizontality of the rays will not affect the fringe pattern observed on the interferometer screen. Bob's interferometer is located at distance d .

According to the scheme of Figure 1, the general nonlocal multi-mode vacuum state of the photons in the experiment is given by:

$$|\Psi\rangle = |\text{vac}\rangle + \epsilon(|s_{po}i_{po}\rangle + |s_{p-}i_{p+}\rangle + |s_{qo}i_{qo}\rangle + |s_{q-}i_{q+}\rangle) \quad (1)$$

where $|\text{vac}\rangle$ is the vacuum ground state; s_{po} and s_{p-} are the photon modes on the $-p_{\text{side}}$ and $-p_{\text{down}}$ signal (Alice's) beams, emanating from point p in the source, as shown in Figure 1, and i_{po} and i_{p+} are the photon modes on the p_{side} and p_{up} idler (Bob's) beams, emanating from the same point in the source. Analogously, for the modes originating from point q on the source, s_{qo} and s_{q-} are the modes on the $-q_{\text{side}}$ and $-q_{\text{down}}$ signal beams, and i_{qo} and i_{q+} are the modes on Bob's q_{side} and q_{up} idler beams. The quantity $\epsilon (\ll 1)$ depends on the pump laser and nonlinearity in the downconverting crystal [8].

Because of the narrowness of the hole, a ray entering it diffracts to enter both slits u and v in the interferometer. In the Schrödinger picture, let the diffracting wavefunction, for some ray $|X\rangle$, be:

$$|X\rangle \longrightarrow \alpha [\sin(\phi/2)|u\rangle + \cos(\phi/2)|v\rangle] + \dots \quad (2)$$

where the \dots indicate other points on the double-slit diaphragm where the photon could fall, but which do not concern us since they do not pass through the double slit. Here α (< 1) depends on h and the cross-section of the slits, ϕ is (some function of) $|X\rangle$'s angle of incidence on the diaphragm as measured from the $+y$ -axis whose origin is at the hole. Note that for a ray perpendicular to the diaphragm, the amplitude for entering both slits is equal. Given the finite width of the downconverted beam, all of which Bob's first lens is assumed to intercept, ϕ will take values between some ϕ_0 (> 0) and $180^\circ - \phi_0$.

By virtue of the direction filter, only the rays p_{side} and q_{side} can fall on Bob's detector. As a result, the (positive mode) electric field $E_B^{(+)}$ at a point x on Bob's detector has contributions from two of the modes: i_{p0} falling on the hole at some angle ϕ , and i_{q0} at angle $180 - \phi$. The phase for each ray depends on the distance along its path.

$$E_B^{(+)} = \alpha \hat{i}_{p0} \left(\sin(\phi/2) e^{ik(d' + \overline{ux})} + \cos(\phi/2) e^{ik(d' + \overline{vx})} \right) + \alpha \hat{i}_{q0} \left(\cos(\phi/2) e^{ik(d' + \overline{ux})} + \sin(\phi/2) e^{ik(d' + \overline{vx})} \right), \quad (3)$$

where the "hatted" quantities represent corresponding annihilation operators, $d' \equiv 2g + \overline{KN} + \overline{Nv} = 2g + \overline{LM} + \overline{Mu}$, and the overline quantities are distances between the named points. The four terms in right hand side of Eq. (3) can be understood as follows. The first term is the product of three amplitudes: for beam p_{side} 's movement (a) from point p to the hole, (b) from the hole to slit u , (c) from slit u to point x on Bob's screen. Similarly with the other terms.

A. Alice measures position

Alice positions her detector on the image plane. A detection at point y (Figure 1) means that the rays $-p_{\text{side}}$ and $-p_{\text{down}}$ were chosen on the signal beam. Alice knows that her photon originated at point p , but its momentum remains indeterminate between directions $-p_{\text{side}}$ and $-p_{\text{down}}$. Correspondingly, the idler photon is left in the correlated ray states p_{side} and p_{up} .

The (positive mode) electric field, $E_A^{(+)}$, of Alice's detector has a contribution from both signal rays, $-p_{\text{side}}$ and $-p_{\text{down}}$, that converge to y . Therefore, Alice's detector is given by the field:

$$E_A^{(+)} = \hat{s}_{p0} e^{ik(2f + \overline{ry})} + \hat{s}_{p-} e^{ik(\overline{py})}. \quad (4)$$

The correlation function for Alice finding her photon at y and Bob his at x is $\langle E_A^{(+)} E_B^{(+)} \rangle$, where $\langle \dots \rangle$ indicates an averaging over the state vector $|\Psi\rangle$ of Eq. (1).

$$\langle E_A^{(+)} E_B^{(+)} \rangle = \epsilon \alpha (\sin(\phi/2) e^{ik(2f + \overline{ry} + d' + \overline{ux})} + \cos(\phi/2) e^{ik(2f + \overline{ry} + d' + \overline{vx})}) \quad (5)$$

The probability P_{AB} of coincident detections between these detectors is given by $|\langle E_A^{(+)} E_B^{(+)} \rangle|^2$, which is:

$$P_{AB} = \epsilon^2 \alpha^2 [1 + \sin(\phi) \cos(\overline{ux} - \overline{vx})]. \quad (6)$$

In Eq. (6), the $\sin(\phi)$ term will be different for different localizations of Bob's photon.

Bob's observed intensity pattern will therefore be an averaged pattern over the closed interval $\phi \in [\phi_0, 180^\circ - \phi_0]$. Integrating over ϕ and assuming for simplicity a flat profile for the converging beam distributed in this range (which is obtained for a laser profile that goes as $g^{-1} \sin^2 \phi$), the ensemble intensity pattern that he finds on his screen is:

$$I_p = I_0 \epsilon^2 \alpha^2 (1 + \cos(\phi_0)) (\cos(\overline{ux} - \overline{vx}), \quad (7)$$

where I_0 is the idler beam intensity. We note that the interference pattern is observed in the single (as against coincidence) count intensity. The reason is that P_{AB} in Eq. (6) does not depend on any Alice variables, whose presence would have, upon being marginalized, resulted in washing out the interference pattern. This is made possible by Bob's filter.

B. Alice measures momentum

Alice positions her detector on the focal plane. A detection at some point means that the signal beam is left with only parallel rays converging to this point. To obtain coincidence events, we need consider only signal rays converging to point m in Figure 1, since Bob's filter permits only rays entangled to them. A detection here implies that the rays $-p_{\text{side}}$ and $-q_{\text{side}}$ were chosen on the signal beam. Correspondingly, the idler photon is left in ray states corresponding to ray p_{side} and q_{side} . Thus, Bob's photon has a definite (horizontal) momentum, but its point of origin is indeterminate between p and q .

Here Alice's detector's electric field is given by:

$$E_A^{(+)} = \hat{s}_{po} e^{ik(2f + \overline{rm})} + \hat{s}_{qo} e^{ik(2f + \overline{tm})} \quad (8)$$

Noting that $\overline{rm} = \overline{tm}$, we find: $P_{AB} = |\langle E_A^{(+)} E_B^{(+)} \rangle|^2$ using Eqs. (1) and (3):

$$P_{AB} = 2\epsilon^2 \alpha^2 (1 + \sin \phi) [1 + \cos(\overline{ux} - \overline{vx})]. \quad (9)$$

Here, too, P_{AB} depends only on the path difference, $\overline{ux} - \overline{vx}$, from the slits to x . It does not depend on any of Alice's variables.

The intensity pattern observed by Bob in the single counts is therefore given by the function:

$$I_m = 2I_0 \epsilon^2 \alpha^2 (1 + \cos \phi_0) [1 + \cos(\overline{ux} - \overline{vx})]. \quad (10)$$

This has a visibility function of 1.0 in contrast to $\cos \phi_0$, found in the case of I_p given in Eq. (7). Furthermore, I_m is about twice more intense than I_p . Therefore the intensity and visibility of Bob's single count interference pattern are affected by what Alice observes. She transmits one classical bit of information nonlocally.

The experiment is essentially a delayed choice experiment [14], as applied to entangled particles instead of a single particle. Alice forces Bob's entangled particle to behave like a wave or particle by measuring a wave (i.e, momentum) or particle (i.e, path) property of her photon. The interesting part is that she may delay her choice of which aspect to manifest until after the photons have left the source.

A more dramatic demonstration of the signaling is obtained by minimizing diffraction at the hole by increasing size h . Position measurement by Alice will result in an idler ray passing through only one of the two slits. No interference will result. On the other hand, her momentum measurement will result in an interference because the optics will ensure that Bob's photon passes through both slits thereby producing an interference. Thus, Bob simply checks for the presence or absence interference pattern to infer Alice's action. One complication here is that a larger hole size would allow non-horizontal momenta to enter the interferometer, thereby reducing the visibility. Therefore the hole cannot be too large. The condition $1 \ll h/\lambda \ll g/s$ ensures that these criteria are satisfied. But it could require larger g than may be feasible for entangled beams of finite coherence length. Nevertheless, the origin of the signaling can be more simply understood for this case, as done in the next subsection.

III. UNDERSTANDING THE CLASSICAL SIGNAL

The no-signaling theorem implies that statistically the outcomes for Bob's particle is independent of Alice's action [11]. It is of interest to know how the above experiment circumvents it. The answer is basically that the proofs of no-signaling assume that both Alice and Bob make complete measurements, whereas in the above experiment, their interferometric measurement is incomplete, because a detection does not uniquely indicate an eigenmode. Furthermore, Bob employs a filter, which restricts his observation to the incomplete measurement projector $\hat{M}_B = |i_{p0}\rangle\langle i_{p0}| + |i_{q0}\rangle\langle i_{q0}|$. Another factor is a subtlety concerning the scope of the complementarity principle in multi-particle interferences.

In a position measurement, Alice collapses $|\Psi\rangle$ with one of the incomplete measurement projectors $\hat{P}_1 = |s_{p0}\rangle\langle s_{p0}| + |s_{p-}\rangle\langle s_{p-}|$ and $\hat{P}_2 = |s_{q0}\rangle\langle s_{q0}| + |s_{q-}\rangle\langle s_{q-}|$. In a momentum measurement, her operators are $\hat{M}_1 = |s_{p0}\rangle\langle s_{p0}| + |s_{q0}\rangle\langle s_{q0}|$ or $\hat{M}_2 = |s_{p-}\rangle\langle s_{p-}| + |s_{q-}\rangle\langle s_{q-}|$. If Alice measures position, the state of photons observed by Bob is $\hat{M}_B \hat{P}_i |\Psi\rangle$. This is given by the statistical mixture:

$$\rho_p = \frac{1}{2} (|s_{p0}i_{p0}\rangle\langle s_{p0}i_{p0}| + |s_{q0}i_{q0}\rangle\langle s_{q0}i_{q0}|). \quad (11)$$

As there are no cross-terms between the paths, Bob observes no interference in this case.

On the other hand, if Alice measures momentum, the state of photons observed by Bob is:

$$\hat{M}_B \hat{M}_1 |\Psi\rangle = (1/\sqrt{2})(|s_{p0}i_{p0}\rangle + |s_{q0}i_{q0}\rangle), \quad (12)$$

since $\hat{M}_B \hat{M}_2 |\Psi\rangle = 0$. A direct application of complementarity would suggest that Bob's rays $|i_{p0}\rangle$ and $|i_{q0}\rangle$ in Eq. (12) cannot produce an interference pattern because their entanglement with the signal photon, whose states $|s_{p0}\rangle$ and $|s_{q0}\rangle$ are mutually orthogonal, makes them distinguishable. This is equivalent to saying that interference is not possible because tracing over the signal states [16] in the density matrix $\hat{M}_B \hat{M}_1 |\Psi\rangle \langle \Psi| \hat{M}_1^\dagger \hat{M}_B^\dagger$ results in ρ_p . *But this conclusion is not supported by the experimentally attested two-particle coincidence interferences* [7,8,15]. The more rigorous approach would be to analyze interference in terms of the phase accumulated by Bob's particle's wavefunction along each path, without reference to external states [17]. Though complementarity is an excellent thumb-rule to elucidate many non-classical effects, it is essentially a qualitative idea, and its use warrents some caution [18].

The observation of two-particle interference implies that the phase contribution to the wavefunction on a path is accounted for by the distance traversed by a ray along its path. No phase (or uniform phase) is picked up at the detector. Bob's filter-interferometer system is crucial as it ensures that only two horizontal modes are allowed (i.e, it implements \hat{M}_B). This fixes the point of Alice's detection in coincidences. Therefore, the relative phase in Bob's wavefunction at the two slits remains constant, permitting the formation of an observable interference pattern on his screen. For the set-up in Figure 1, the relative phase vanishes. Classical signaling is the direct consequence of the distinguishability of $\hat{M}_B \hat{M}_1 |\Psi\rangle$ in Eq. (12) from ρ_p in Eq. (11). We note that the single mode probabilities for states $|i_{p0}\rangle$ and $|i_{q0}\rangle$ are the same for both cases. Thus, the no-signaling theorem, within the scope of its implicit assumption, is not violated. Also, for the same reason, no violation of probability conservation occurs.

IV. DISCUSSION

The above experiment aims to prove a much stronger condition about nonlocal correlations than does Bell's theorem, in two ways. First: unlike Bell's theorem, it does not assume the reality of underlying variables; just the tested principles of quantum mechanics and quantum electrodynamics suffice. Second: the nonlocal influence is shown to transmit classical information, which means that the correlations are not uncontrollable. Of course, this leads to the problematic situation that the effective speed v_{eff} of the transmission of this nonlocal classical signal can be made arbitrarily large. In one sense this need not be surprising: for quantum mechanics is a non-relativistic theory. The no-signaling theorem is based on quantum mechanical unitarity and assumptions of quantum measurement rather than relativistic signal locality. If the instant of Alice's choice is t_a and that of Bob's measurement is t_b , where $t_b \geq t_a$, then $v_{\text{eff}} = (d + 4f)/(t_b - t_a)$, where the upper limit occurs in the situation where Alice delays her choice until just before her photon reaches her. Since this can be made arbitrarily large by increasing $4f$ and d and/or decreasing the time difference, suggesting that nonlocality does not prohibit a superluminal classical signal, it is of interest to examine factors inhibiting such a possibility.

The situation is not improved by considering a no-collapse scenario like the relative-state (or many-worlds) interpretation [19], because each branching universe would have to contend with the classical signal. Requiring collapse to be subluminal (even simply non-instantaneous) would imply significant changes to quantum theory, and furthermore permit non-conservation of entangled quantities. By demonstrating a classical transfer of information, the above experiments would corroborate the objective nature of state vector reduction.

It appears that to restore causality we would need the light to somehow decohere into disentangled momentum pointer states [20] before reaching Bob's double-slit so that he will always find a Young's double-slit interference pattern irrespective of Alice's action. But it is not clear how such a decoherence can be brought about. Perhaps somehow spacetime itself would act as a measuring environment to the system, thereby decohering it, in order to safeguard its own causal structure? Such an explanation is related to an incompleteness in quantum mechanics as a formal axiomatic theory [21], and would probably require new axioms in the theory. But it would also reveal an unexpected connection between quantum information and decoherence. In any case, the technical feasibility of the above described thought experiment permits a facile test for nonlocal communication of the type claimed in this paper.

V. CONCLUSION

The question raised in the title of this article is answered in the affirmative. It is unclear how this is to be reconciled with signal locality. Perhaps this points to the need for new physics to understand state vector "collapse", more so in nonlocal cases.

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